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Wang

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(54) **METHOD FOR GENERATING A MACHINE HEARTBEAT**

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(60) Provisional application No. 61/493,412, filed on Jun. 3, 2011.

(51) **Int. Cl.**

G06F 15/18	(2006.01)
G06F 11/00	(2006.01)
G06F 9/46	(2006.01)
G06F 11/30	(2006.01)

(52) **U.S. Cl.**

CPC ***G06F 9/46*** (2013.01); ***G06F 11/3006*** (2013.01); ***G06F 11/3082*** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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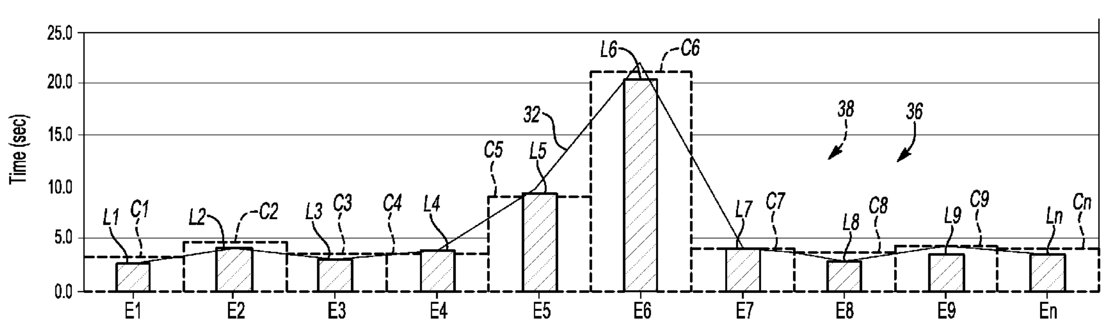
(57) **ABSTRACT**

A method and system for generating a heartbeat of a process including at least one machine configured to perform a process cycle consisting of a plurality of timed events performed in a process sequence under an identified condition includes determining the duration of each of the timed events during the process cycle performed under the identified condition, ordering the durations of the plurality of timed events in the process sequence, and generating a heartbeat defined by the ordered durations of a process cycle. The identified condition may be one of a design intent, baseline, learnt, known, current or prior condition. The variance of the heartbeat between a first and at least a second identified condition may be analyzed to monitor and/or control the process or machine. The system may display the process heartbeat information and may generate a message in response to the heartbeat and/or variance thereof.

20 Claims, 4 Drawing Sheets



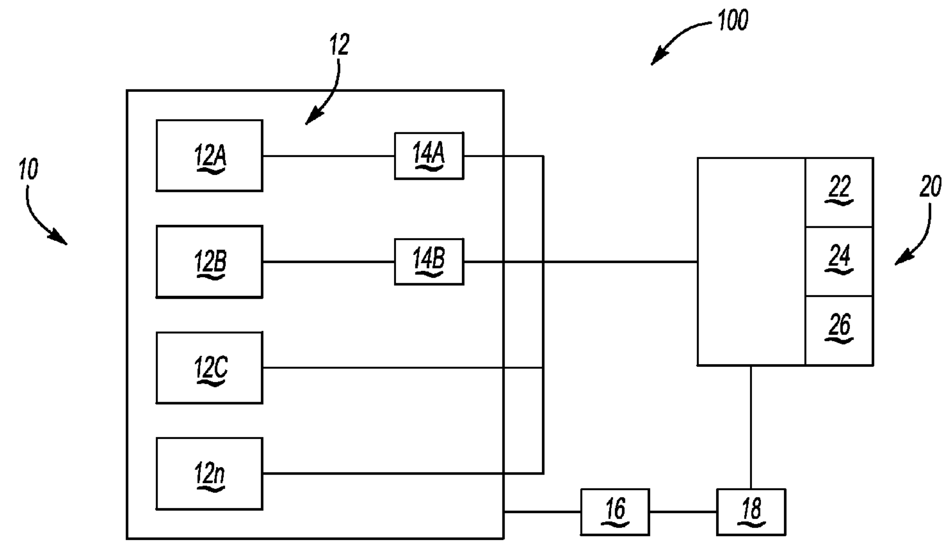

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Fig-1

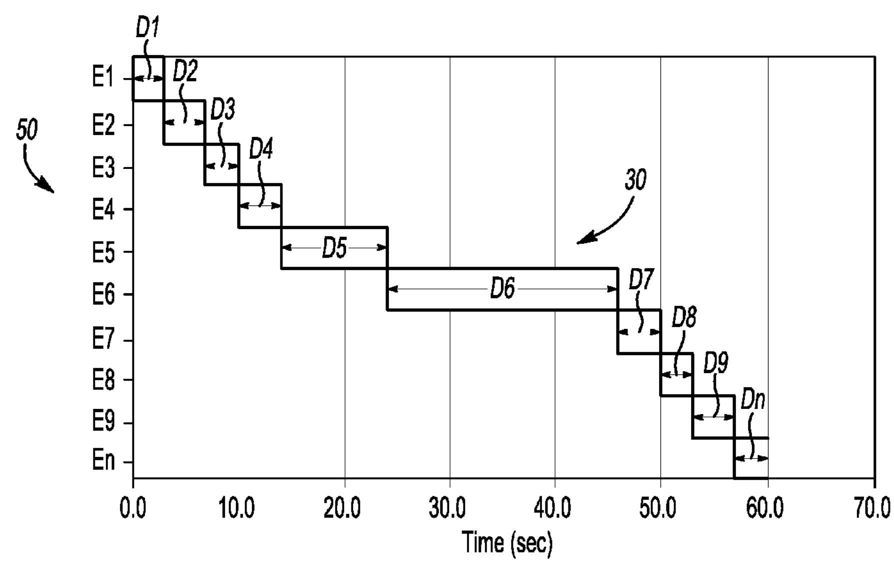
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Fig-2

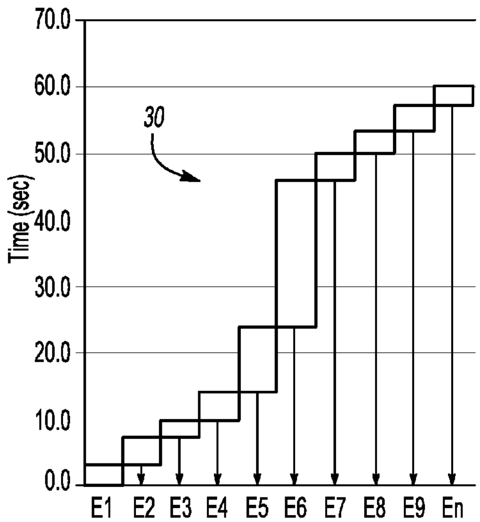


Fig-3A

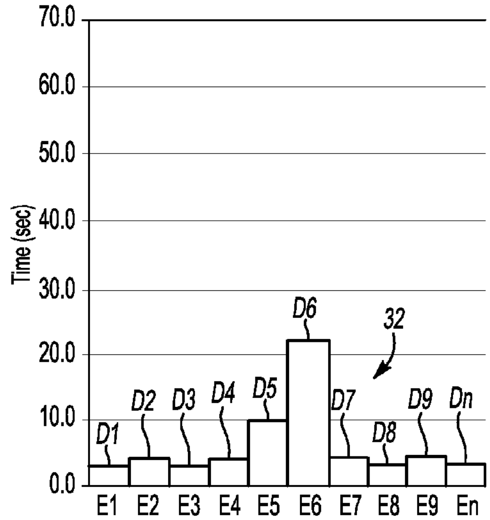


Fig-3B

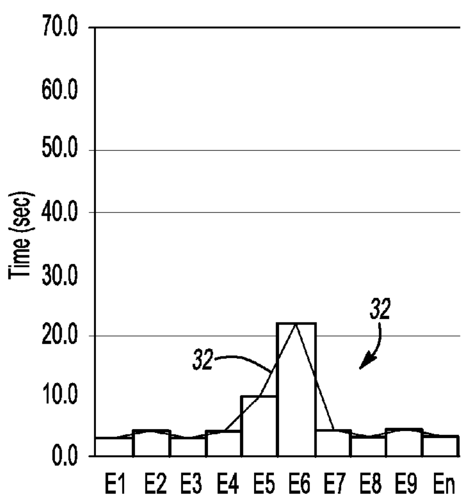


Fig-3C

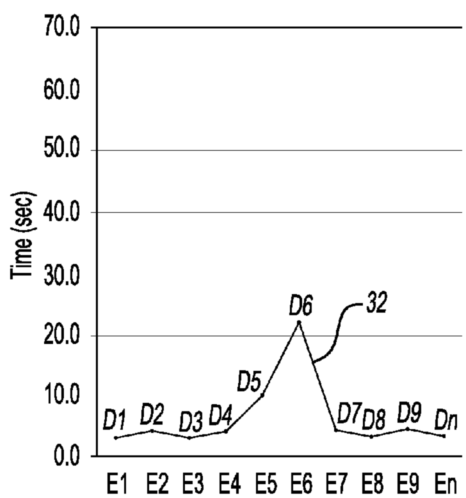
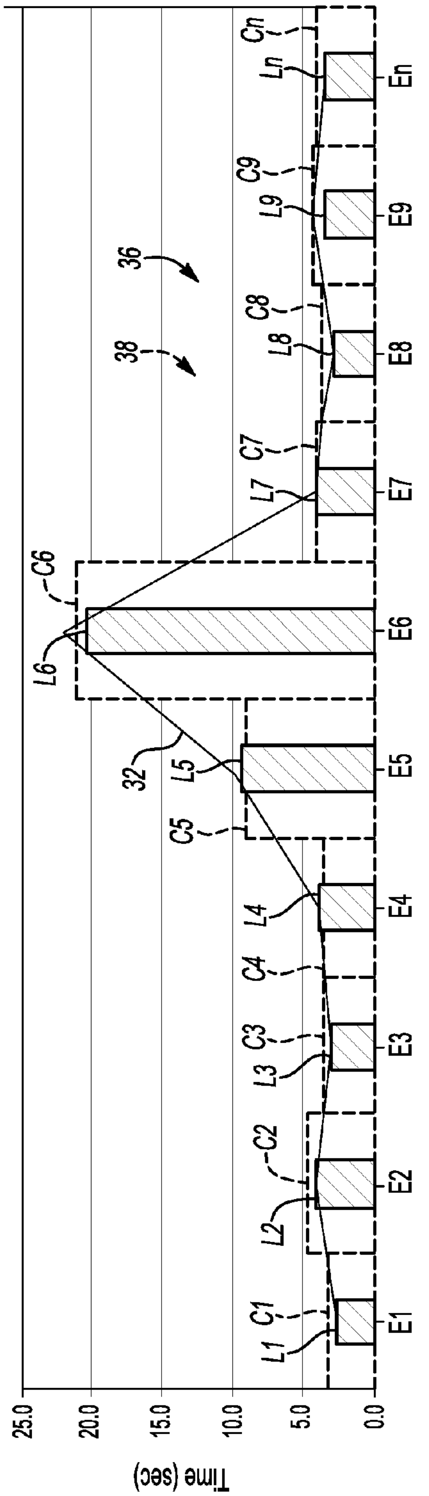


Fig-3D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L1
L2
L3
L4
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L6
L7
L8
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C9
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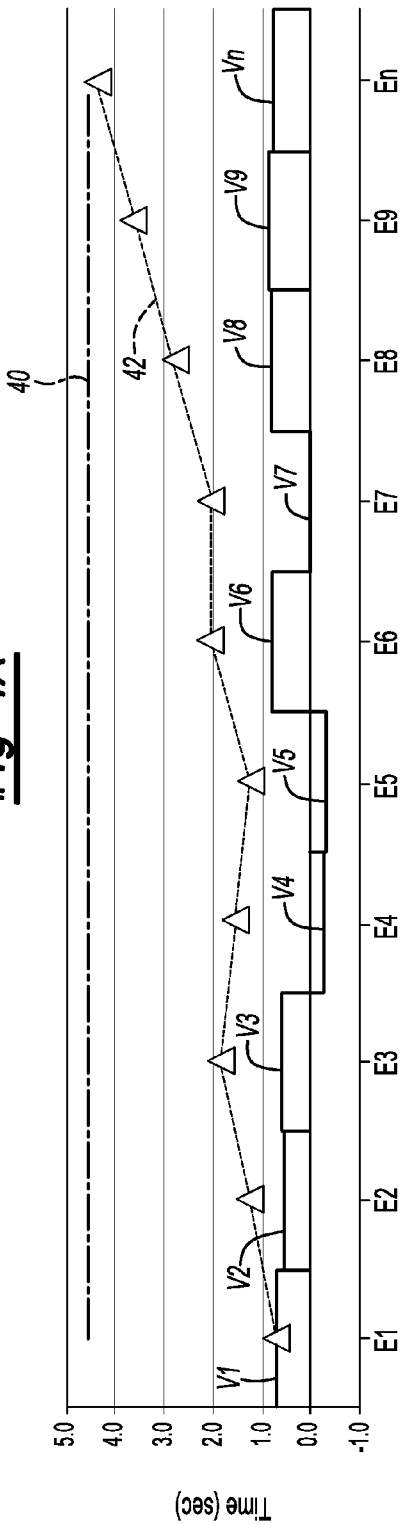
32
36
38

Fig-4A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E7
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E9
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V1
V2
V3
V4
V5
V6
V7
V8
V9
Vn
40
42

Fig-4B

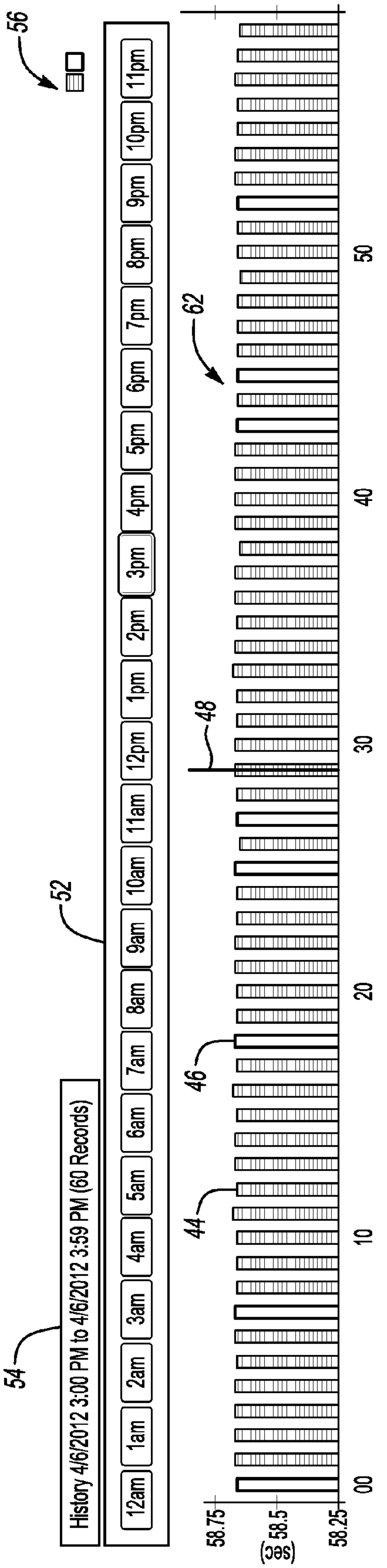
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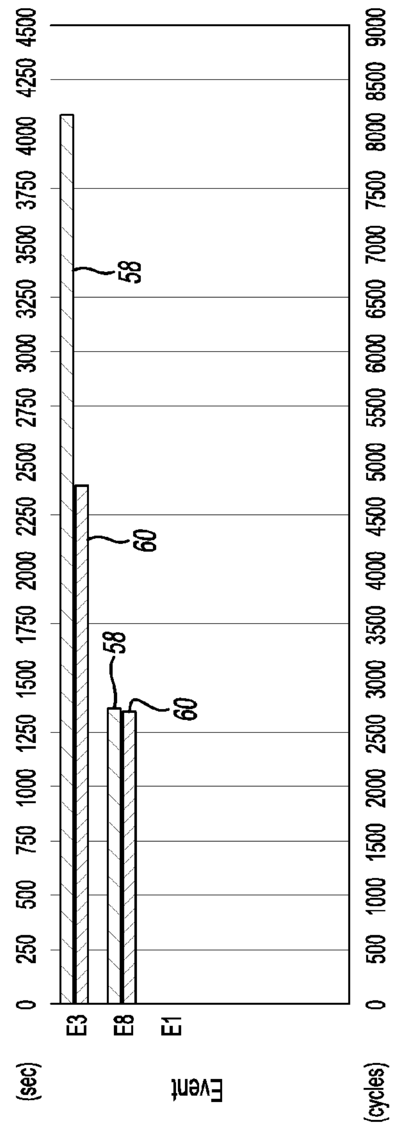
Fig-5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4250
4500
Event
E3
E8
E1
58
60
58
60
(cycles)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000

Fig-6

METHOD FOR GENERATING A MACHINE HEARTBEAT

CROSS REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. patent application Ser. No. 13/486,275 filed Jun. 1, 2012, and U.S. Provisional Application 61/493,412 filed Jun. 3, 2011, which are hereby incorporated by reference in their entirety.

TECHNICAL FIELD

The present disclosure relates generally to process control methods, and more particularly to a method and a system for generating a heartbeat of a process.

BACKGROUND

Most machinery operates by performing a predetermined set of events, which may also be referred to as tasks, in an ordered sequence to provide a process outcome. These events are precisely sequenced and timed according to the design intent of the process being performed by the machinery. These timed events may be initiated, controlled, monitored and/or measured by one or more computational devices, which may include controllers such as programmable logic controllers and/or programmable automation controllers, or the like.

As the process is performed, the duration of a timed event may vary from one process cycle to another as the process conditions change, which may vary the duration of the process cycle, the throughput and/or efficiency of the machinery, and/or the process outcome. Variation in the duration of a timed event may indicate a process condition trending toward a downtime condition, such as a tool or equipment failure, a process condition requiring maintenance to prevent productivity loss, a potential quality issue, or other condition affecting the process outcome. Known predictive methods of monitoring machinery and/or automated processes, such as machinery vibration analysis, may not sufficiently discriminate sources of variation to effectively predict process conditions which may require intervention to prevent downtime, productivity loss, or quality issues.

SUMMARY

A system and method are provided for generating a machine "heartbeat," where the heartbeat is defined by event durations of a plurality of timed events of a process performed by the machinery, where the event durations are ordered in the process event sequence. The heartbeat may be represented by a data sequence or graphically by a pattern. In one example, the pattern may be a bar graph pattern. In another example, the pattern may be a continuous line defined by the ordered event durations, where the "ordered event durations" are the event durations of the timed events of the process arranged in process sequence, e.g., in the order the timed events are performed by the process. The machine heartbeat may be used to measure, monitor and/or control the process by providing a comparator for evaluation of variation in event duration from one process cycle to another. Detailed understanding of variation in the event duration of the timed events from one process cycle to another process cycle performed by the machinery may be used to control and/or improve the process outcome and/or machinery capability, provide predictive or preventive identification of concerns through event duration analysis, enable causal analysis to identify causes of beneficial variation in event duration and/or eliminate or minimize causes of detrimental variation in event duration, and/or identify and/or initiate preventive interventions such as preventive maintenance or pre-failure process shutdown. The machine heartbeat may be generated for a process including a plurality of events performed in sequence by the process machinery, wherein the machinery includes at least one machine. A method for monitoring a process may include generating a series of heartbeats including a current heartbeat and one or more prior heartbeats, which may include a baseline heartbeat, a learnt heartbeat, and other prior heartbeats wherein each respective heartbeat is defined by the duration of the events of a process cycle performed under an identified condition, comparing the variance between the heartbeats and/or identifying process trends based on differences in the event durations and/or duration variances between a current heartbeat and a plurality of prior heartbeats.

The method for generating a heartbeat of a process including at least one machine configured to perform a process cycle, wherein the process cycle consists of a plurality of timed events performed in a process sequence, includes identifying a baseline duration of each of the plurality of timed events, ordering the baseline durations of the plurality of timed events in the process sequence, and generating a baseline heartbeat defined by the ordered baseline durations of a baseline process cycle. The baseline heartbeat may correspond to the design intent condition of the process, such that baseline duration of each of the timed events is the design intent duration of that timed invent identified for the process.

The method may further include generating a learnt heartbeat defined by the ordered learnt durations of a learnt process cycle, where the learnt process cycle is performed under a known condition or set of conditions. In one example, the known set of conditions of the learnt process cycle corresponds to machinery and process parameters which most closely replicate the design intent of the process. In another example, the learnt cycle is a known "good cycle" where the process outcome and/or process parameters are known to be within acceptable limits. A learnt event variance may be determined between the learnt duration and the baseline duration of each respective event in the process sequence, and may be used to generate a cumulative learnt variance. The learnt event variance and/or cumulative learnt variance may be used to establish acceptable limits for the process, against which a current heartbeat of the process can be evaluated, wherein the current heartbeat is defined by a current process cycle performed under a then current process condition, allowing real time monitoring, control and preventive or predictive analysis of the process and/or machinery.

The system and method may include generating a message, which may be provided to or displayed by a user interface or transmitted to a messaging device or to the machinery, for example, as an instruction, alert or shutdown signal. The system may include a user interface configured to display one or more heartbeats and/or related data, messages and signals, where a heartbeat may be displayed as one or more of a data table, a heartbeat data sequence, a bar graph pattern, and a continuous line pattern.

The above features and advantages, and other features and advantages, of the present disclosure are readily apparent from the following detailed description of some of the best modes and other particular, embodiments for carrying out the invention, as defined in the appended claims, when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of a system for generating the heartbeat of a process performed by at least one machine;

FIG. **2** is a schematic illustration of a sequence of events chart showing a process cycle including a plurality of timed events in sequenced order and a baseline duration of each of the timed events;

FIG. **3**A is a schematic illustration of rotating the sequence of events chart of FIG. **2** and shifting each of the plurality of baseline event durations to originate at the horizontal axis to order the baseline event durations in process sequence order to form the bar graph shown in FIG. **3**B;

FIG. **3**B is a schematic illustration of a baseline heartbeat of the process cycle of FIG. **2** defined by the ordered baseline event durations, ordered as illustrated in FIG. **3**A, where the pattern of the baseline heartbeat is graphically represented by the pattern of the bar graph formed by the ordered baseline event durations;

FIG. **3**C is a schematic illustration showing the baseline heartbeat of the process cycle of FIG. **2**, where the pattern of the baseline heartbeat is graphically represented by the pattern of the bar graph of FIG. **3**B and by the pattern of a continuous line connecting the ordered baseline event durations;

FIG. **3**D is a schematic illustration of the baseline heartbeat of the process cycle of FIG. **2** where the pattern of the baseline heartbeat is graphically represented by the pattern of the continuous line connecting the ordered baseline event durations;

FIG. **4**A is a schematic illustration comparing the baseline heartbeat of FIG. **3**D to a learnt heartbeat and a current heartbeat;

FIG. **4**B is a schematic illustration of event variance and cumulative variance between the learnt and current heartbeats of FIG. **4**A;

FIG. **5** is a schematic illustration of a sample history of process cycle duration information; and

FIG. **6** is a schematic illustration showing over cycle frequency and accumulated variance by timed event.

DETAILED DESCRIPTION

Referring to the drawings, wherein like reference numbers correspond to like or similar components throughout the several figures, FIG. **1** shows a system, generally indicated at **100**, for generating a "heartbeat" of a process, where the heartbeat is defined by event durations of a plurality of timed events of a process performed by the machinery, where the event durations are ordered in the process event sequence. The heartbeat may be represented by a data sequence or graphically by a pattern. In one example, the pattern may be a bar graph pattern. In another example, the pattern may be a continuous line defined by the ordered event durations, where the "ordered event durations" are the event durations of the timed events of the process arranged in process sequence, e.g., in the order the timed events are performed by the process. The machine heartbeat may be used to measure, monitor and/or control the process by providing a comparator for evaluation of variation in event duration from one process cycle to another. Detailed understanding of variation in the event duration of the timed events from one process cycle to another process cycle performed by the machinery may be used to control and/or improve the process outcome and/or machinery capability, provide predictive or preventive identification of concerns through event duration analysis, enable causal analysis to identify causes of beneficial variation in event duration and/or eliminate or minimize causes of detrimental variation in event duration, and/or identify and/or initiate preventive interventions such as preventive maintenance or pre-failure process shutdown.

The process, generally indicated at **10**, includes machinery generally indicated at **12** configured to perform a process cycle **30** illustrated by the sequence of events chart shown in FIG. **2**. The process cycle **30** consists of a plurality of timed events E**1** . . . En, performed in a process sequence **50** beginning with a first event or task E**1** and ending with a last event or task En. Each of the timed events E**1** . . . En is characterized by an event duration, e.g., the length of time to perform the event, which may vary based on the operating condition of the process **10** and/or machinery **12**. As shown in FIG. **1**, in a non-limiting example, the machinery **12** includes at least one machine, which may be one or more of the machines **12**A, **12**B, **12**C . . . **12***n*, configured to perform the process **10**. The machinery **12** may include a controller, which may be one or more of the controllers **14**A, **14**B, in communication with at least one of the machines **12**A . . . **12***n*. The controller **14**A, **14**B may be configured as a programmable logic controller (PLC), a programmable automation controller (PAC), or the like. Each of the machines **12**A . . . **12***n* and/or the machinery may be of any type configurable to perform at least one "timed event" in a sequence of events defining a process cycle of the process **10**, where a "timed event" as that term is used herein is an event having a defined start and stop such that the duration of the event is measurable or otherwise determinable. The machinery **12** may be controlled by a controller, may be automated, or may otherwise be operated in a manner such that the duration of the timed event performed during a process cycle is determinable.

The system **100** may include a server **20** in communication with the machinery **12** and configured to receive event duration data from the machinery **12**, and to generate a heartbeat for the process **10** including the machinery **12** using the event duration data. The server **20** may include one or more applications **22** adaptable to process the event duration data received from the machinery **12**. The server **20** may include a memory **24** and a database **26** for receiving, storing, and/or providing the event duration data and data derived therefrom including variance and trend data, heartbeat data, heartbeat history, etc. within the system **100**, and a central processing unit (CPU) (not shown) for executing the applications **22**. The memory **24**, at least some of which is tangible and non-transitory, may include, by way of example, ROM, RAM, EEPROM, etc., of a size and speed sufficient, for example, for executing the applications **22**, storing the database **26**, and/or communicating with the machinery **12**, controllers **14**A, **14**B, and/or devices **16**, **18**.

Processing the event duration data using the applications **26** may include, by non-limiting example, one or more of generating a heartbeat based on the event duration data; associating the event duration data and/or heartbeat with the time the event duration data was provided and/or an operating condition of the machinery **12** and/or process **10** at the time the event duration data was provided; associating the event duration data with a particular machine **12**A . . . **12***n* of the machinery **12**, a particular event E**1** . . . En, a machine condition, a time of the event or other event identifying information; analyzing the event duration data to generate a heartbeat, an event variance, and/or a cumulative variance; analyzing the event duration data and/or data derived therefrom to identify process trends, abnormalities or other data patterns; storing the event duration data and other data derived therefrom, including but not limited to an event variance, a cumulative variance, a heartbeat, trend data, with associated information such as event identifying information, etc. in a database **26**; generating a message or signal based on the event duration data; and/or transmitting the message or signal to the machinery **12** via the controllers **14**A, **14**B or directly, to a user interface device **18**, or to another messaging device **16** which may be in communication with the machinery **12** or process **10**.

The examples provided herein are non-limiting. For example, it would be understood that the functions of the server **20** may be provided by a single server, or may be distributed among multiple servers, including third party servers, and that the data within the system **100** may be provided by databases configured other than as described for the database **26**. For example, the event duration data related to machine **12**A may reside in a shared database stored in the controller **14**A in communication with the server **20**. The database **26** may be distributed among multiple servers, including third party servers, in communication with each other and the server **20** through a network (not shown), such as the Internet, and/or directly.

FIGS. **2** through 3D illustrate a method for generating a machine heartbeat, which may be, in the example shown, a baseline heartbeat **32** (see FIG. **3**D), defined by event duration data D**1** . . . Dn provided for the sequential timed events E**1** . . . En of a process cycle **30** (see FIG. **2**) to be performed by the machinery **12**. In the example shown, the baseline heartbeat **32** and the baseline event duration data D**1** . . . Dn corresponds to the design intent of the process cycle **30**.

As illustrated by the sequence of events chart shown in FIG. **2**, performing a single process cycle **30** of the process **10** consists of performing the first timed event E**1**, then performing the second timed event E**2**, and so on, until each of the plurality of timed events E**1** . . . En are performed in the process sequence **50** indicated by the ordering of events E**1** . . . E**2** shown on the sequence of events chart to complete the process cycle **30**. Each timed event E**1** . . . En in the baseline process cycle **30** is characterized by a baseline event duration D**1** . . . Dn, which in the example shown is the length of time to perform the event as specified by the design intent of the process **10**. In a non-limiting example, where the values indicated are for illustrative purposes, each respective baseline duration D**1** . . . Dn corresponding to a respective timed event E**1** . . . En is shown graphically in FIG. **2** and in the data table identified as Table 1.

baseline data sequence (D**1**, D**2**, D**3**, D**4**, D**5**, D**6**, D**7**, D**8**, D**9**, Dn), which, using the illustrative values shown in Table 1, corresponds to the ordered baseline event durations (3, 4, 3, 4, 10, 22, 4, 3, 4, 3). Referring now to FIGS. **3**A-**3**B, the baseline heartbeat **32** may be graphically generated by rotating the sequence of events chart of FIG. **2** to order the plurality of timed events E**1** . . . En along the horizontal axis (as shown on the page) in the process sequence **50**, and by shifting each of the plurality of baseline event durations D**1** . . . Dn as indicated by the arrows on FIG. **3**A, such that each event duration D**1** . . . Dn originates at the horizontal axis, to form the bar graph shown in FIG. **3**B and corresponding to the baseline heartbeat data sequence (D**1**, D**2** . . . . Dn) defined by the ordered baseline event durations D**1** . . . Dn. FIG. **3**B shows the pattern formed by the bar graph, which provides a graphical representation of the baseline heartbeat **32**. Other graphical representations of the baseline heartbeat **32** may be defined by the ordered baseline event durations D**1** . . . Dn. For example, FIG. **3**C shows the baseline heartbeat **32** graphically represented by a continuous line, where the pattern of the continuous line is defined by the ordered baseline event durations D**1** . . . Dn, and corresponds to the bar graph pattern generated in FIG. **3**B and shown again in FIG. **3**C. FIG. **3**D shows the heartbeat **32** graphically represented by the continuous line, graphically showing the rhythm of the baseline heartbeat **32** defined by the ordered baseline event durations D**1** . . . Dn. It would be understood that the baseline heartbeat **32** may be expressed by the baseline heartbeat data sequence (D**1**, D**2**, . . . , Dn), graphically represented by the bar graph pattern of FIG. **3**B defined by the ordered baseline event durations, or graphically represented by a continuous line pattern of FIG. **3**D defined by the ordered baseline event durations, wherein either graphical representation (bar graph pattern or continuous line pattern) shall be considered equivalent to the other and to the heartbeat data sequence illustrated by Table 1 in defining the baseline heartbeat **32** of the baseline process cycle **30**.

As described previously, a heartbeat of the process **20** may be defined by the ordered event durations of a process cycle performed under an identified condition, where the event

TABLE 1

Event (E)	E1	E2	E3	E4	E5	E6	E7	E8	E9	En
Baseline Duration (D)	3.0	4.0	3.0	4.0	10.0	22.0	4.0	3.0	4.0	3.0

A heartbeat of the process **10** may be defined by the event durations of a process cycle performed under an identified condition, where the event durations of the identified process cycle are ordered in the process sequence **50**, to provide "ordered baseline durations" of the identified process cycle. As referred to herein, the "ordered event durations" are the event durations of an identified process cycle arranged in the order of the process sequence **50** to define the heartbeat of the identified process cycle, and an "identified condition" is the condition under which the process cycle is performed to provide the event duration data from which a respective heartbeat is generated. For example, referring to the baseline process cycle **30** shown in FIG. **2**, the identified condition of the baseline process cycle **30** is a baseline condition, which may be the design intent condition of the process **10** and/or the machinery **12**. A baseline heartbeat **32** (shown graphically in FIGS. 3B-3D) is defined by the ordered baseline event durations shown in order of the process sequence **50** in Table 1, where the baseline heartbeat **32** may also be expressed as a

durations of the identified process cycle are ordered in the process sequence **50**, to provide "ordered baseline durations" of the identified process cycle. It would be understood that the actual duration of a timed event during performance of the process **10** may vary from one process cycle to another based on the operating condition of and/or operating variables in the process **10** and/or the machinery **12** during that process cycle. Operating variables may include operating environmental factors such as temperature or humidity, machine maintenance or wear, tooling set-up or wear, workpiece fixturing, workpiece dimensional and/or material variation, variability in power supply, lubrication, or hydraulic pressure provided to the machinery, etc.

FIG. **4**A shows a series of heartbeats **32**, **36**, **38** generated for the process **10**, where each of the heartbeats **32**, **36**, **38** varies from another of the heartbeats **32**, **36**, **38** due to variability in the operating condition of the process **10**, wherein each of the heartbeats **32**, **36**, **38** may be associated with an identified operating condition of the process **10** during the process cycle from which the heartbeat **32**, **36**, **38** is derived. The first heartbeat shown in FIG. **4**A is the baseline heartbeat **32**, which is graphically represented in FIG. **4**A as a continuous line, and the baseline process cycle **30** (see FIG. **2**) from which the baseline heartbeat **32** is generated corresponds to the design intent condition of the process **10**. A second heartbeat is graphically represented in FIG. **4**A as a bar graph formed of the cross-hatched bars defined by a second heartbeat data sequence (L**1**, L**2**, L**3** . . . Ln) is generally indicated at **36**. The second heartbeat **36** in the present example may also be referred to as a learnt heartbeat **36**, where the learnt process cycle (not shown) from which the learnt heartbeat **36** is generated corresponds to a known condition of the process **10**, and the learnt event durations L**1**, L**2** . . . Ln correspond to the timed events E**1**, E**2** . . . En performed in the process sequence **50** by the learnt process cycle.

The known condition of the learnt process cycle may be, for example, a process cycle representing optimized process and machine conditions, e.g., conditions most closely replicating design intent process cycle **30**. The known optimized (learnt) process cycle and learnt heartbeat **36** derived therefrom may be used, for example, to determine the best possible process performance to be expected during actual operation of the process **10**, as compared with the original design intent of the process represented by the baseline heartbeat **32**. By way of example, the learnt process cycle may be a known good cycle, where a "good cycle" as used herein, is a process cycle which is within acceptable operating parameters determined for the process **10** and/or machinery **12**. For example, a known good cycle may be a learnt process cycle performed within the design specification of the process **10**, e.g., performed within an acceptable tolerance from the design intent process cycle **30**. In another example, the known condition of the learnt process cycle may be characterized by one or more machine set-up parameters, key characteristics of the fixturing or other operating characteristics of the machine, operating environment characteristics such as operating temperatures, process outcome parameters such as finished workpiece characteristics, etc. which have been measured and recorded to establish a known set of conditions defining the learnt heartbeat **36**.

The learnt process cycle may be performed by the process **10** after determining the baseline process cycle **30** from the design intent of the process **10**, such that the learnt process cycle is considered to be performed subsequent to the baseline process cycle **30**, and the learnt heartbeat **36** is a subsequent heartbeat of the process **10** relative to the prior baseline heartbeat **32**. By comparing a subsequent heartbeat generated for a subsequent identified condition to a prior heartbeat generated for a prior condition, where subsequent and prior refer to the relative time at which the respective identified process cycle was performed from which each respective heartbeat is generated, the performance of the process **10** and/or the machinery **12** may be monitored, evaluated and/or controlled.

Comparing a subsequent heartbeat to a prior heartbeat may include, for example, determining a variance between the event duration of an event during the subsequent process cycle from which the subsequent heartbeat is derived, and the event duration of the same event during a prior process cycle from which the prior heartbeat is derived. For example, the learnt event duration L**1** of the timed event E**1** measured during the learnt process cycle performed by the machinery **12** may be compared with the baseline event duration D**1** of the timed event E**1** determined from the design intent process cycle specified for the machinery **12**. The variance between the learnt event duration L**1** and the baseline event duration D**1** may be referred to as the learnt event variance for the timed event E**1**, where the learnt event variance may be used to establish the expected variance of the duration of the timed event E**1** from the baseline (design intent) duration of the timed event E**1** during process operation. Similarly, the variance between learnt event duration L**2** and the baseline event duration D**2** may be determined for the second timed event E**2** in the event sequence of the process **10**, and so on, such that the variance between each of the learnt events durations L**1** . . . Ln and the respective baseline event durations D**1** . . . Dn may be determined for each of the timed events E**1** . . . En in the process sequence **50** of the process **10**. The learnt event variances for the timed events E**1** . . . En can then be used, for example, to provide an expected event variance for comparison with subsequent process cycles. A tolerance or limit for subsequent event variances may be established for each of the learnt event variances for the timed events E**1** . . . En, which may be used in evaluating subsequent event durations, where variance of a subsequent event duration is in excess of the learnt event variance and/or a tolerance or limit established for the learnt event variance may cause the system **100** to generate a message, which may be, for example, an indication that the event corresponding to the excess event duration be further monitored or evaluated, an indication that maintenance of the machinery **12** performing the event is indicated or required, an indication that the cycle time of the process **10** may be changing in a manner which may impact a process outcome including for example, process productivity, quality or uptime, a signal to the process **10** and/or machinery **12** to modify operating conditions which may include shutting down an operation to prevent an undesirable change in process outcome, which may include shutting down an operation to prevent damage to or failure of the machinery **12** and/or related downtime, or triggering an alarm or alert.

Comparing a subsequent heartbeat to a prior heartbeat may include, in another example, determining the cumulative variance between a subsequent heartbeat defined by a subsequent process cycle, and a prior heartbeat defined by a prior process cycle. Referring again to FIGS. **4**A and **4**B, a learnt cumulative variance between the learnt heartbeat **36** and the baseline heartbeat **32**, where the learnt heartbeat **36** is a subsequent heartbeat relative to the prior baseline heartbeat **32**, may be determined by summing the learnt event variances of the timed events E**1** . . . En to determine a learnt cumulative variance for the duration of the learnt process cycle relative to duration of the baseline process cycle. The learnt cumulative variance, which corresponds to line **40** in the example of FIG. **4**B, can then be used, for example, to provide an expected cumulative variance for a subsequent heartbeat, such as a current heartbeat **38** shown in FIG. **4**A, relative to the baseline heartbeat **32**, where the expected cumulative variance corresponds to the expected variance of the total duration of the subsequent process cycle relative to the total duration of the baseline process cycle **30**. The learnt cumulative variance **40** may be established as a limit **40**, as shown in FIG. **4**B, for comparison with or evaluation of a subsequent cumulative variance defined by a subsequent heartbeat corresponding to a subsequent process cycle. The system **100** may be configured such that when a subsequent cumulative variance of a subsequent event duration is in excess of the learnt event variance and/or limit **40**, the system **100** may generate a message, which may be, for example, an indication that the machinery **12** and/or process **10** be further monitored or evaluated, an indication that maintenance of the machinery **12** is indicated or required, an indication that the cycle time of the process **10** may be changing in a manner which may impact a process outcome including for example, process productivity, quality or uptime, a signal to the process **10** and/or machinery **12** to modify operating conditions which may include shutting down an operation to prevent an undesirable change in process outcome or to prevent a damage to or failure of the machinery **12** and/or related downtime, or triggering an alarm or alert.

Referring again to FIG. **4**A, a third heartbeat is generally indicated at **38** and is graphically represented in FIG. **4**A as a bar graph formed of the broken-line bars defined by a third heartbeat data sequence (C**1**, C**2**, C**3** . . . Cn). The third heartbeat **38** in the present example may also be referred to as a current heartbeat **38**, where the current process cycle (not shown) from which the current heartbeat **38** is generated corresponds to a current condition of the process **10**, and the learnt event durations C**1**, C**2** . . . Cn correspond to the timed events E**1**, E**2** . . . En performed in the process sequence **50** by the current process cycle. The current process cycle may be performed by the process **10** after the learnt process cycle and the baseline process cycle **30**, such that the current process cycle is considered to be performed subsequent to the learnt and baseline process cycles, and the current heartbeat **38** is a subsequent heartbeat of the process **10** relative to the learnt heartbeat **36** and relative to the baseline heartbeat **32**, where the learnt and baseline heartbeats **36**, **32** may be referred to as prior heartbeats of the process **10** relative to the current heartbeat **38**.

The current process cycle is performed under a current condition, e.g., the actual operating condition of the process **10** and/or machinery **12** existing at the time the current process cycle is performed. As such the current condition includes and/or reflects changes in process operating parameters of the process **10**, machine operating parameters of the machinery **12**, workpiece characteristics of the workpiece (not shown) being processed by the machinery **12**, or other sources of process variation, which may include, for example, variation in environmental conditions influencing process performance and/or output such as temperature, humidity, incoming power source characteristics, or the like existing at the time the current process cycle is performed. By comparing the current heartbeat **38** to at least one prior heartbeat **32**, **36**, the performance of the process **10** and/or the machinery **12** may be monitored, evaluated and/or controlled in real time, e.g., at the time the current process cycle defining the current heartbeat **38** is performed. Further, by comparing a subsequent heartbeat, such as the current heartbeat **38**, to a plurality of prior heartbeats which may include the baseline heartbeat **32**, the learnt heartbeat **36**, and/or another current heartbeat generated subsequent to the learnt heartbeat **36** and prior to the current heartbeat **38**, where the another current heartbeat is a prior heartbeat relative to the current heartbeat **38**, process trends may be evaluated and/or identified based on the comparison of at least one of the current event variance and the current cumulative variance of the current heartbeat **38**.

Comparing the current heartbeat **32** to the learnt heartbeat **36** may include, for example, determining a current event variance between the current event duration of a timed event determined during the current process cycle, and the learnt event duration of the same event determined during the learnt process cycle. For example, and referring to FIGS. **4**A and **4**B, the current event duration C**1** of the timed event E**1** measured during performance of the current process cycle may be compared with the learnt event duration L**1** of the timed event E**1** determined from the learnt process cycle. The variance between the current event duration C**1** and the learnt event duration L**1** for the timed event E**1** is shown in FIG. **4**B as the current event variance V**1**, where the current event variance V**1** may be used to evaluate the current process condition by comparing the current event variance V**1** to the learnt event variance for the timed event E**1**.

Similarly, the current event variance V**2** between current event duration C**2** and the learnt event duration L**2** may be determined for the second timed event E**2** in the event sequence of the process **10**, and so on, such that the current event variance V**1** . . . Vn between each of the current event durations C**1** . . . Cn and the respective learnt event durations L**1** . . . Ln may be determined for each of the timed events E**1** . . . En in the process sequence **50** of the process **10**. The current event variances V**1** . . . Vn for the timed events E**1** . . . En can be evaluated and used to monitor the current operating condition of the process **10** and/or the machinery **12**, which may include generating a message using the system **100** in response to one or more of the current event variances V**1** . . . Vn, and/or process trends identified by the system **100**. The message may be, for example, an indication that the respective event corresponding to the current event variance V**1** . . . Vn to which the message is related may required further monitoring or evaluation, an indication that maintenance of the machinery **12** performing the respective event is indicated or required, an indication that the cycle time of the process **10** may be changing in a manner which may impact a process outcome, and/or a signal to the process **10** and/or machinery **12** to modify operating conditions which may include shutting down an operation to prevent damage to the machinery **12** and/or process downtime.

Referring again to FIGS. **4**A and **4**B, a current cumulative variance between the current heartbeat **32** and the learnt heartbeat **36** may be determined by summing the current event variances V**1** . . . Vn of the timed events E**1** . . . En to generate the current cumulative variance **42** for the current process cycle relative to the learnt process cycle shown in FIG. **4**B. The current cumulative variance **42** may be compared at any point in the event sequence **50** (E**1**, E**2**, . . . En) to determine whether the current cumulative variance **42** at that point in the event sequence **50** of the current process cycle has exceeded a limit. The limit may be, in the example shown in FIG. **4**B, the limit **40** defined by the learnt cumulative variance. The system **100** may be configured such that when the current cumulative variance **42** exceeds the limit **40** at any point in the event sequence **50**, the system **100** may generate a message, which may be, for example, a maintenance indication, a cycle time indication, a signal to modify and/or shutdown a portion or all of the process **10** and/or machinery **12**, or the like, as previously described herein.

The baseline, learnt and current heartbeats **32**, **36**, **38** defined respectively by baseline, learnt and current process cycles performed by the process **10**, and prior heartbeats (not shown) defined by prior process cycles performed by the process **10** prior to the current heartbeat **38** may be collected, stored and analyzed using the system **100**. Collecting and storing the heartbeats may include collecting and storing the heartbeat data sequences of each respective heartbeat, which may include, for example, a baseline heartbeat data sequence (D**1**, D**2** . . . Dn), a learnt heartbeat data sequence (L**1**, L**2** . . . Ln), and/or a current heartbeat data sequence (C**1**, C**2** . . . Cn) used to respectively define the baseline, learnt and current heartbeats **32**, **36**, **38**. Analyzing the heartbeats may include determining one or more of event variances and/or a cumulative variance between respective heartbeats, and/or comparing a determined variance to a variance limit or tolerance established for the determined variance. For example, analyzing the current heartbeat **38** may include determining one or more current event variances V**1** . . . Vn, comparing a current event duration C**1** . . . Cn with a respective learnt event duration L1 . . . Ln or a respective baseline event duration D1 . . . Dn, determining a current cumulative variance 42 and/or comparing the current cumulative variance 42 with a cumulative variance limit 40, and the like.

The variance between the baseline, learnt, and current heartbeats 32, 36, 38 may be used to measure, monitor and/or control the process 10 by comparing the variation in the current duration C1 of a respective event, for example, event E1, to the baseline and/or learnt duration D1, L1 of the respective event. In another example, the current cumulative variation 42 of the plurality of events E1 . . . En comprising the process cycle 30 may be compared to the learnt cumulative variation 40 of the plurality of events E1 . . . En. Detailed understanding of variation of event duration of the timed events E1 . . . En and/or the cumulative variance of the plurality of timed events performed by a first identified process cycle of the process 10 relative to at least a second identified process cycle may be used to control and/or improve the process 10 performed by the machinery 12, by identifying significant fluctuations in event duration through variance and/or trend analysis of the heartbeat defined by the first identified process cycle compared to at least a second identified heartbeat defined by a respective identified process, where the at least second identified heartbeat(s) may including one or more prior heartbeats, which may include the learnt and/or baseline heartbeats 36, 32.

Referring again to FIG. 1, the system 100 may be configured to output information related to the process 10, machinery 12, including heartbeat information to an output device, which may be one of the devices 16, 18. Each of the devices 16, 18 may be in communication with or operatively connected to one or more of the server 20, the machinery 12, the controllers 14A, 14B, and/or to each other, in a wireless or wired configuration, and may be configured to exchange information and/or data therebetween. In one example, the device 18 may be a user interface device configured to output information related to the process 10, machinery 12, event duration data and/or process heartbeats derived therefrom. The outputted information may include, by way of non-limiting example, a display of one or more process heartbeats or heartbeat history, which may be displayed textually and/or graphically, event duration information, identified process conditions corresponding to a heartbeat which may include identified machine or process parameters, heartbeat variance information including event variance, cumulative variance, variance analysis, trend analysis and other information derived from the event duration information collected from the process 10 and/or machinery 12, messages, alerts, alarms, etc. The output device 18 may include at least one of a visual display, audio output, report generator, printer, data port, or other output device configured to receive data from the server 20, through which data may be transferred to a user or another device.

By way of example, the output device 16 may be configured as a signaling or messaging device, and may be configured to output a signal or message to one or more of the process 10, machinery 12, server 20, output device 16 or other device (not shown) in communication with the messaging device 16. The output device 16 may be configured to output the signal or message as one or more of an electronic, visual, or audible signal or message. The outputted signal or message may include a signal, message or instruction sent to the process 10 and/or machinery 12 to modify or shutdown a portion or all of the process 10 and/or machinery 12, where the signal may be generated in response to a heartbeat defined by the process 10 and/or machinery 12, or information derived from analysis of the heartbeat. In one example, the messaging device 16 may be configured to communicate the signal or message to a user device (not shown), which may be a portable user device such as a smart phone, notebook, laptop or other computing device, to communicate the signal or message to a user of the user device, such that the user may initiate an action in response to the signal or message, where the action may be one of a maintenance action or other action affecting the process 10 and/or machinery 12. The example shown in FIG. 1 is intended to be non-limiting, and it would be understood that the functions performed by one or both of the output devices 16, 18 may be performed by another of the devices included in the system 100, such as the server 10, controller 14, etc.

Referring now to FIG. 5, shown is a non-limiting example of a process information display which may be generated by and outputted from the system 100, using the timed event duration data collected from the process 10 over a period of time. The display shown in FIG. 5 may be displayed, for example, by one of the output devices 16, 18, a controller 14A, 14B, or outputted to another device for display. The process information display of FIG. 5 shows a time series 62 of a sampling of process cycle duration measurements taken over a sample period indicated at 54. The sample period 54 may be selected for display from a time period menu 52. In the example shown, the time period menu 52 provides one hour sample period intervals to select from, and a 24 hour period is shown. In the example shown, the sample period 54 is a one hour period from 3:00 pm to 3:59 pm, and the time series 62 is configured to show process cycle duration samples taken at one minute intervals. For example, sample 44 represents the duration of the process cycle performed at 3:13 pm, and sample 46 represents the duration of the process cycle performed at 3:18 pm. It would be understood that the display may be configured for other durations of time period menus 52 and/or sample periods 54, other sample frequencies, etc., to provide different levels of discrimination of the information displayed. For example, the sample period 54 may be a ten minute period with a sampling interval of 20 seconds, to provide a more detailed view of variability in the duration of the process cycles of the process 10.

The process cycle duration, as shown in FIG. 5, represents the total duration of a process cycle. Using the example of the baseline cycle 30 shown in FIG. 2 and the example data provided in Table 1, the total duration of the baseline process cycle 30 would be the summation of the durations D1 . . . Dn of the timed events E1 . . . En comprising the process cycle 30. For the example shown in FIG. 2 and Table 1, the total duration of the baseline process cycle 30 would be 60, e.g., the summation of the baseline event durations (3, 4, 3, 4, 10, 22, 4, 3, 4, 3). Referring again to FIG. 5, a cursor or selector 48 may be configured to allow a user to select a process cycle sample in the series 62 to retrieve additional information. In the example of FIG. 5, the selector 48 has selected the process cycle performed at 3:32 pm, which may prompt the system 100 to provide detailed information, which may include, for example, a display of event duration information similar to that shown in FIGS. 4A and/or 4B, for the selected process cycle.

Each sample in the time series 62 may be visually coded according to a key 56 to provide additional information to the user viewing the display. In the example shown, the key 56 includes a cross-hatched bar and a solid bar, each which may represent a different condition. For example, the samples displayed by a cross-hatched bar may represent samples, such as the sample 44, for which the heartbeat variance is within an acceptable limit. Samples displayed by a solid bar may represent samples, such as the sample 46, where the heartbeat variance is outside an acceptable limit. Further visual indicators may be included. For example, the solid bar may be a first color to indicate an event variance is outside an acceptable limit for the sample, and the solid bar may be a second color to indicate the cumulative variance is outside an acceptable limit for the sample. The example shown in not intended to be limiting. By displaying a time series **62** of process cycle durations over a sample period **54**, a visual indication of the variability of and trending in process cycle duration over multiple process cycles performed by the process **10** may be provided. Such an analysis may be useful, for example, to look for trends corresponding to changes in operating conditions of the process **10** and/or machinery **12**, which may include changes in environmental factors such as temperature or power fluctuations from one time period to another, process or tooling changes, set-up or maintenance events, changes in incoming material or workpiece parameters, etc.

Referring now to FIG. **6**, shown is another non-limiting example of a process information display which may be generated by and outputted from the system **100**, using the timed event duration data collected from the process **10** over a period of time. The display shown in FIG. **6** may be displayed, for example, by one of the output devices **16**, **18**, a controller **14**A, **14**B, or outputted to another device for display. The process information display of FIG. **6** shows an over cycle frequency **58** and an accumulated variance **60** for one or more individual timed events in the process sequence **50**. The over cycle frequency **58** refers to the number of times the duration of the timed event has exceeded the duration of a reference event measured during performance of a reference cycle. By example, the over cycle frequency of the timed event E**3** shown in FIG. **6** may represent the number of times (frequency) during a sample period (not shown) of process operation that the current duration C**3** of each the timed event E**3** performed during the sample period exceeded the learnt duration L3 of the event E**3**, where the reference cycle is the learnt cycle. The accumulated variance **60** refers to the summation of the event variances of the timed event over the sample period relative to the reference event. By example, the accumulated variance of the timed event E**3** shown in FIG. **6**, where the reference cycle is the learnt cycle, would be the summation of the current variances V**3** measured for the process cycles performed during the sample period, which would indicate the total productive time loss attributable to variance of the timed event E**3** during the sample period.

Other information may be provided by FIG. **6**. For example, the average variance per over cycle may be visually approximated for each timed event. As shown for timed event E**8**, during the sample period shown, the variance of timed event E**8** averaged approximated 0.5 seconds per over cycle. The timed events may be displayed in ranked order according to the event's frequency of over cycles and/or accumulated variance, for example, in the order E**3**, E**8**, E**1** in FIG. **6**, to facilitate identification of those events to be prioritized for investigation and/or corrective action. Other displays, including displays of tabular data and/or other graphical analysis, of the event duration, cycle duration, heartbeat and/or data derived therefrom may be provided, and the examples shown are not intended to be limiting.

The detailed description and the drawings or figures are supportive and descriptive of the invention, but the scope of the invention is defined solely by the claims. While the best mode, if known, and other embodiments for carrying out the claimed invention have been described in detail, various alternative designs and embodiments exist for practicing the invention defined in the appended claims.

The invention claimed is:

1. A method for generating a heartbeat of a process, the method comprising:

performing a process cycle of a process;

wherein the process cycle is performed by at least one machine;

measuring a duration of each of a plurality of timed events performed in a process sequence during the process cycle;

ordering the durations of the plurality of timed events in the process sequence; and

generating, via a server, a heartbeat defined by the ordered durations.

2. The method of claim **1**, wherein the process cycle is a learnt process cycle performed under a learnt condition, the method comprising:

measuring a learnt duration of each of a plurality of timed events performed in the process sequence during the learnt process cycle;

ordering the learnt durations of the plurality of timed events in the process sequence; and

generating, via a server, a learnt heartbeat defined by the ordered learnt durations.

3. The method of claim **2**, wherein the learnt condition includes at least one known process parameter.

4. The method of claim **2**, further comprising:

identifying a baseline duration of each of the plurality of timed events of the process cycle;

ordering the baseline durations of the plurality of timed events in the process sequence; and

generating, via the server, a baseline heartbeat defined by the ordered baseline durations of the process cycle.

5. The method of claim **4**, wherein the baseline duration of each of the plurality of timed events is a design intent duration of the respective event.

6. The method of claim **4**, further comprising:

determining a learnt event variance between the learnt duration and the baseline duration for each of the plurality of timed events.

7. The method of claim **4**, further comprising:

determining a learnt cumulative variance between the learnt heartbeat and the baseline heartbeat.

8. The method of claim **2**, further comprising:

performing a current process cycle under a current condition;

measuring a current duration of each of the plurality of timed events performed in the process sequence during the current process cycle;

ordering the current durations of the plurality of timed events in the process sequence; and

generating, via the server, a current heartbeat defined by the ordered current durations.

9. The method of claim **8**, further comprising:

determining a current event variance between the current duration and the learnt duration for each of the plurality of timed events.

10. The method of claim **9**, further comprising:

determining a current cumulative variance between the current heartbeat and the learnt heartbeat.

11. The method of claim **8**, further comprising generating a message in response to the current heartbeat.

12. The method of claim **11**, wherein the message is at least one of:

a maintenance indicator;

a cycle time indicator; and

a shutdown signal.

13. A method of generating a heartbeat of a process, the method comprising:

performing, via at least one machine, a plurality of process cycles of a process;

wherein each respective process cycle is performed under a respective condition at a respective time and;

generating, via a server, a respective heartbeat for each respective process cycle;

associating each respective heartbeat of the plurality of heartbeats with at least one of the respective time and the respective condition; and

comparing each respective heartbeat with at least one other heartbeat of the plurality of heartbeats.

14. The method of claim **13**, wherein the process cycle includes a plurality of timed events performed in a process sequence; and

wherein generating each respective heartbeat comprises:

measuring a respective duration of each of the plurality of timed events performed in the process sequence during the respective process cycle;

ordering the respective durations of the plurality of timed events in the process sequence; and

generating, via the server, a respective heartbeat defined by the ordered current durations.

15. The method of claim **13**, further comprising:

identifying a baseline duration of each of the plurality of timed events of the process cycle;

ordering the baseline durations of the plurality of timed events in the process sequence; and

generating, via the server, a baseline heartbeat defined by the ordered baseline durations of the process cycle.

16. The method of claim **15**, further comprising:

comparing each respective heartbeat with the baseline heartbeat.

17. The method of claim **13**, wherein comparing each respective heartbeat of the plurality of heartbeats with another heartbeat of the plurality of heartbeats includes:

determining, for the duration of each event of the plurality of timed events, an event variance between the duration of the event of the respective heartbeat and the duration of the event of the at least one other heartbeat.

18. The method of claim **13**, wherein comparing each respective heartbeat of the plurality of heartbeats with another heartbeat of the plurality of heartbeats includes:

determining a cumulative variance between the respective heartbeat and the at least one other heartbeat.

19. The method of claim **13**, further comprising:

identifying a process trend defined by the plurality of heartbeats.

20. The method of claim **13**, further comprising:

generating a message in response to one of:

an event variance between the respective heartbeat and the at least one other heartbeat of the plurality, and

a current cumulative variance between the respective heartbeat and the at least one other heartbeat of the plurality.

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